Validation of an Analytical Snow BRDF Model Using PARASOL Multi-Angular and Multispectral Observations

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***Abstract*—We describe a two-parameter model for the reflectance of snow and test it against multispectral and multi-angular observations. The first parameter of the model is proportional to the effective snow grain size. The second parameter accounts for the impact of soot and other pollutants on snow absorption. The model is analytical and is easily inverted against a set of multispectral observations. To test the ability of the model to reproduce snow reflectance, we use a multispectral and multidirectional set of measurements acquired by the POLDER-3 instrument onboard the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) satellite. We selected pure snow targets over Greenland and Antarctica. The model reproduces the main features of the snow angular reflectance: 1) the snow reflectance generally decreases toward longer wavelengths, 2) the reflectance has maximum in the forward scattering direction at large view zenith angles, and 3) the reflectance variations in the perpendicular plane are small compared to those observed in the principal plane. The coefficient of correlation between the results of simulations and the measurements exceeds 85% in most of cases.**

***Index Terms*—Antarctica, Greenland, light scattering, Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL), POLDER, radiative transfer, reflectance, snow.**

I. Introduction

REMOTE sensing of cryosphere and also atmospheric aerosol, cloud, and trace gases in polar regions from a satellite requires detailed knowledge of the snow angular reflectance function (RF). The RF as a whole is 4-D. It depends on the directions of incidence $\vec{n}_s(\vartheta_s, \phi_s)$ and observation $\vec{n}_v(\vartheta_v, \phi_v)$. Here, ϑ_s and ϑ_v are incidence and viewing zenith angles, respectively (both equal to zero at nadir direction), while ϕ_s and ϕ_v are the respective azimuthal angles. For the horizontally homogeneous surfaces, the RF depends not separately on the angles ϕ_s and ϕ_v but only on the relative azimuthal angle (RAA) defined as $\varphi = \phi_v - \phi_s$.

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TABLE I
Imaginary Part of the Ice Refractive Index $\chi(\lambda)$ [17] for a Set of Wavelengths λ That Are Commonly Used for Satellite Remote Sensing

$\lambda, \mu m$	χ
0.412	2.5e-9
0.443	1.7e-9
0.490	1.8e-9
0.565	3.0e-9
0.670	1.9e-8
0.865	2.5e-7
1.02	2.25e-6
1.24	1.2e-5
1.61	3.3e-4

There are several analytical models for snow RF. In [5], Koenderink and Richards proposed a three-parameter snow RF model, which is only applicable to the visible part of the spectrum (negligible absorption). Warren *et al.* [18] proposed a parameterization with respect to RAA and the viewing zenith angle. A total of 12 coefficients are used for a best fit of the data. Degünther and Meerkötter [4] used the four-parameter version of the snow RF and additionally multiplied it by a factor depending on the RAA to account for the strong forward scattering by snow. The model based on the radiative transfer equation solution for spherical snow grains was studied by Aoki *et al.* [1]. Kokhanovsky and Zege [6] proposed an analytical radiative transfer model to describe the snow RF with just one free parameter, which can be assessed from the measurements itself. The model was validated using ground observations [7], [10] and showed a good agreement with measurements acquired over pure snow deposited on a frozen lake. Kokhanovsky *et al.* [10] generalized the model on the case of snow contaminated by soot.

The task of this letter is to validate a new bidirectional reflectance distribution function asymptotic radiative transfer (ART) model presented by Kokhanovsky *et al.* [10] and test

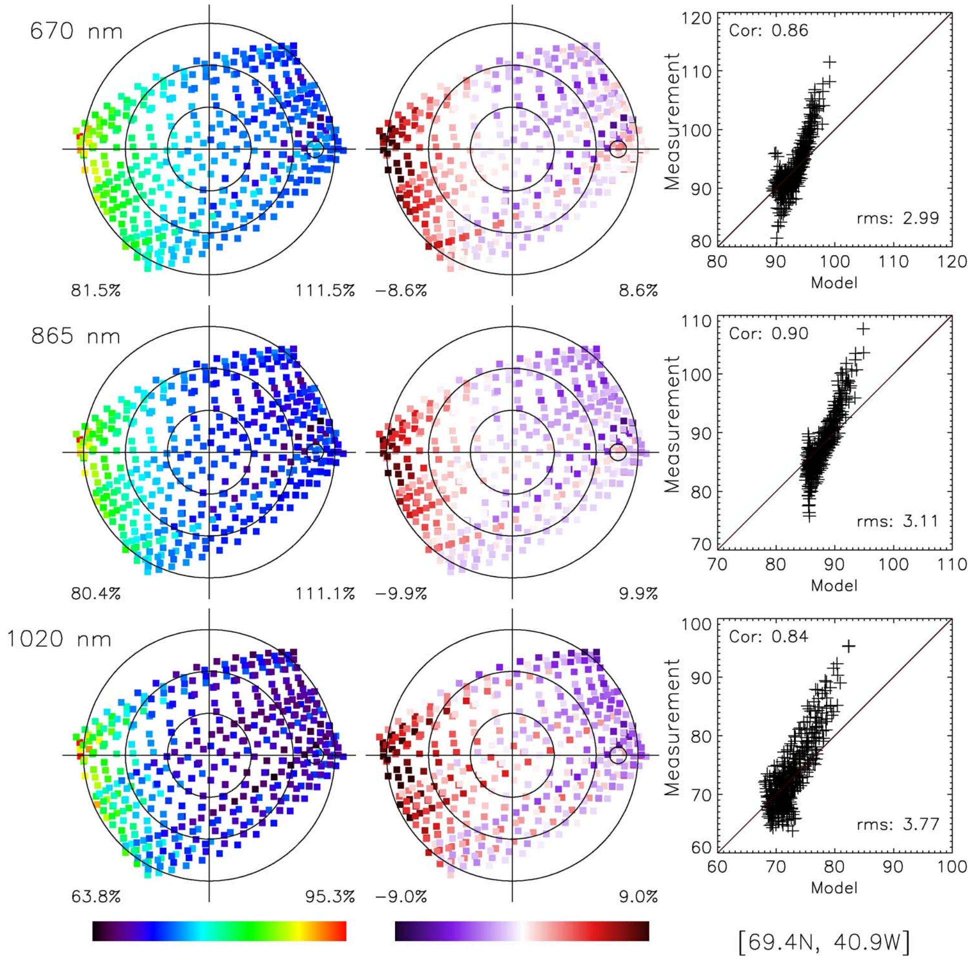

Fig. 1. Comparison of modeling results with satellite reflectance observations acquired during May 2006 for a site in central Greenland. First column shows the measured reflectance (in percent) with a variable range that is shown at the bottom of each plot. The principal plane is the horizontal line, and the sun direction is shown as a small circle on the right side of the plot (solar zenith angle varies between 48 and 54° for the set of measurements). The large circles indicate the viewing zenith angles of 20, 40, and 60°. The central column is the difference between the measurements and the two–parameter ART model (see text). The right column shows a scatter plot between the measurements and the model. The parameter L was inverted based on the 1020-nm reflectance with a result of 3.6 mm, and the second parameter was derived from the 670-nm measurements with a result of $M = 5.5 \times 10^{-8}$.

its ability at reproducing the multispectral and multidirectional POLDER-3 measurements. POLDER-3 is an instrument onboard the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) satellite launched by the French Space Agency CNES on December 18, 2004. In the next section, we describe the model. The comparison with the observations is shown and discussed in Section III.

II. Snow Reflectance Model

The snow reflectance model is given in terms of the reflection function $R = \pi I_{refl}/\mu_s F_0$ used extensively by the remote sensing community. Here, I_{refl} is the intensity of reflected light, F_0 is the solar light flux on the plane perpendicular to the incident beam, and $\mu_s = \cos\vartheta_s$. Fresh snow in the visible is close to a Lambertian reflector with an average reflectance that is close to 1 and relative directional variations that are much smaller than those of other land surfaces such as bare soil or vegetation [3]. However, although the snow reflectance is close to Lambertian, it does show some directional signatures that must be quantified and modeled. This is done in the framework of the model introduced by Kokhanovsky and Zege [6]. We present this model in a slightly modified notation [10]

$$R(\mu_s, \mu_v, \varphi) = R_0(\mu_s, \mu_v, \varphi) \times \exp\left[-\alpha K_0(\mu_s) K_0(\mu_v)/R_0(\mu_s, \mu_v, \varphi)\right] \quad (1)$$

$$R_0(\mu_s, \mu_v, \varphi) = \frac{a + b(\mu_s + \mu_v) + c\mu_s\mu_v + p(\theta)}{4(\mu_s + \mu_v)}$$

$$K_0(\mu) = \frac{3}{7}(1 + 2\mu) \quad (2)$$

$$a = 1.247 \quad b = 1.186 \quad c = 5.157$$

$$p(\theta) = 11.1\exp(-0.087\theta) + 1.1\exp(-0.014\theta) \quad (3)$$

$$\cos\theta = -\mu_s\mu_v + s_s s_v \cos\varphi, \mu_s = \cos(\vartheta_s)$$

$$\mu_v = \cos(\vartheta_v) \quad s_s = \sin(\vartheta_s) \quad s_v = \sin(\vartheta_v) \quad (4)$$

$$\alpha = \sqrt{\gamma L} \quad (5)$$

where $\gamma = 4\pi(\chi + M)/\lambda$, χ is the imaginary part of ice refractive index, λ is the wavelength. The value of L is approximately equal to $13d$, where d is the average optical diameter of snow

grains and M is directly proportional to the mass concentration of pollutants in snow as discussed by Kokhanovsky *et al.* [10]. The scattering angle θ in (3) is given in degrees. The imaginary part of refractive index of ice χ at several wavelengths is presented in Table I [17]. This model with slight changes can be used also for other weakly absorbing semi-infinite turbid media (see, e.g., Kokhanovsky [8]). The model in its general form was formulated by Rozenberg [14] and developed further by several groups (see, e.g., Zege *et al.* [19]).

$R_0(\mu_s, \mu_v, \varphi)$ is the reflection function of a semi-infinite non-absorbing medium and the exponential term in (1) accounts for the decrease of reflectance due to possible light absorption effects in snow. One may set typical values for L and M for a particular snow type or targeted area. However, in satellite remote sensing applications, the ground conditions are generally not known. In such case, L and M shall be considered as free parameters that can be derived from a set of measurements. We hypothesize that two free parameters are sufficient to model the spectral and angular distributions of snow reflectance for any combination of observation and illumination geometries and at least till the wavelength 1.24 μm, where the assumption of weak absorption holds.

In the validation exercise that is discussed in this letter, we use the measurements at wavelengths 670 nm and 1020 nm for the inversion procedure. As the snow absorption depends primarily on the grain size for the longer wavelength, the 1020-nm reflectance measurements are used to invert the snow grain size. Once the snow grain size is retrieved, the shorter wavelength measurements can be used to estimate the absorption of light by pollutants (the parameter M) in snow. We have attempted an iterative inversion process, but found that the results did not change significantly after the first iteration. The value of M is proportional to the imaginary part of the refractive index of pollutants [10], which may depend on the wavelength. We ignore this dependence because it is very weak in the visible and near infrared for many absorbing substances including soot.

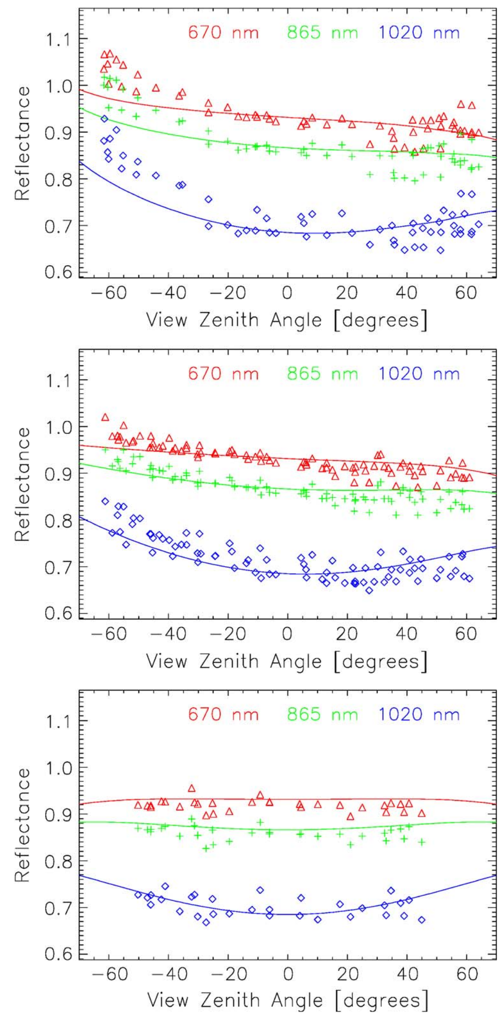

Fig. 2. Comparison of measurements (symbols) and model (lines) for the same target as in Fig. 1. These figures are based on the same data as in Fig. 1, but limited to the principal (top), 45–135° azimuth (middle), and perpendicular (bottom) planes. We take all measurements with $|\theta_{\mathrm{v}} \sin(\phi - \phi_0)| < 5°$, where ϕ_0 is the reference azimuth(e.g., 45° and 135° for the figure in the middle). Negative values of viewing zenith angles correspond to the relative azimuth ϕ equal to 0, 45, and 90°, respectively. Positive values of viewing zenith angles correspond to relative azimuth angles larger than 90°. In each figure, the top to bottom symbols and line correspond to 670, 865, and 1020 nm. The case of the RAA equal to zero (at $\vartheta_s = \vartheta_v$) corresponds to the glint region.

III. Comparison of Model Results With Satellite Data

The successful application of a similar model to Moderate Resolution Imaging Spectroradiometer grain size retrievals was presented by Tedesco and Kokhanovsky [15], [16], Lyapustin *et al.* [11], and Kokhanovsky *et al.* [10]. Negi and Kokhanovsky [13] applied the model to Hyperion sensor data. In addition, Kokhanovsky and Schreier [9] and Kokhanovsky *et al.* [10] applied the ART model to the Advanced Along-Track Scanning Radiometer (AATSR) and the MEdium Resolution Imaging Spectrometer (MERIS) observations. Both MERIS and AATSR are on board European Space Agency Environmental Satellite. In all cases, only single view observations were used so that the validity of directional signatures provided by the model could not be assessed. POLDER-3 onboard PARASOL provides measurements of top-of-atmosphere reflectance at 443, 490, 565, 670, 763, 765, 865, 910, and 1020 nm for up to 16 observation directions of the same ground scene with the moderate spatial resolution of 6 × 7 km. The field of view is 43° along track and 51° cross track. Therefore, a comprehensive validation of various ground target reflectance models can be performed as shown by Maignan *et al.* [12].

The analysis of POLDER multidirectional data against a set of analytical models has shown that the so-called Ross–Li model, with a correction for the hot-spot effect [3], is the best among the models that were tested [12]. This model reproduces the directional variations of the measured reflectance with an RMS error that is typically 0.005 in the visible and 0.01 in the near infrared. Surprisingly, the model is also able to reproduce the directional signature of snow, although its directional signature is very different from that of vegetation or bare soil. However, this result is achieved to the expense that the model parameters (i.e., the linear coefficients of the kernels) take unphysical values. In addition, the Ross–Li–HS model uses three parameters for each wavelength, which reduces its predictive capabilities. We recall that the ART model discussed

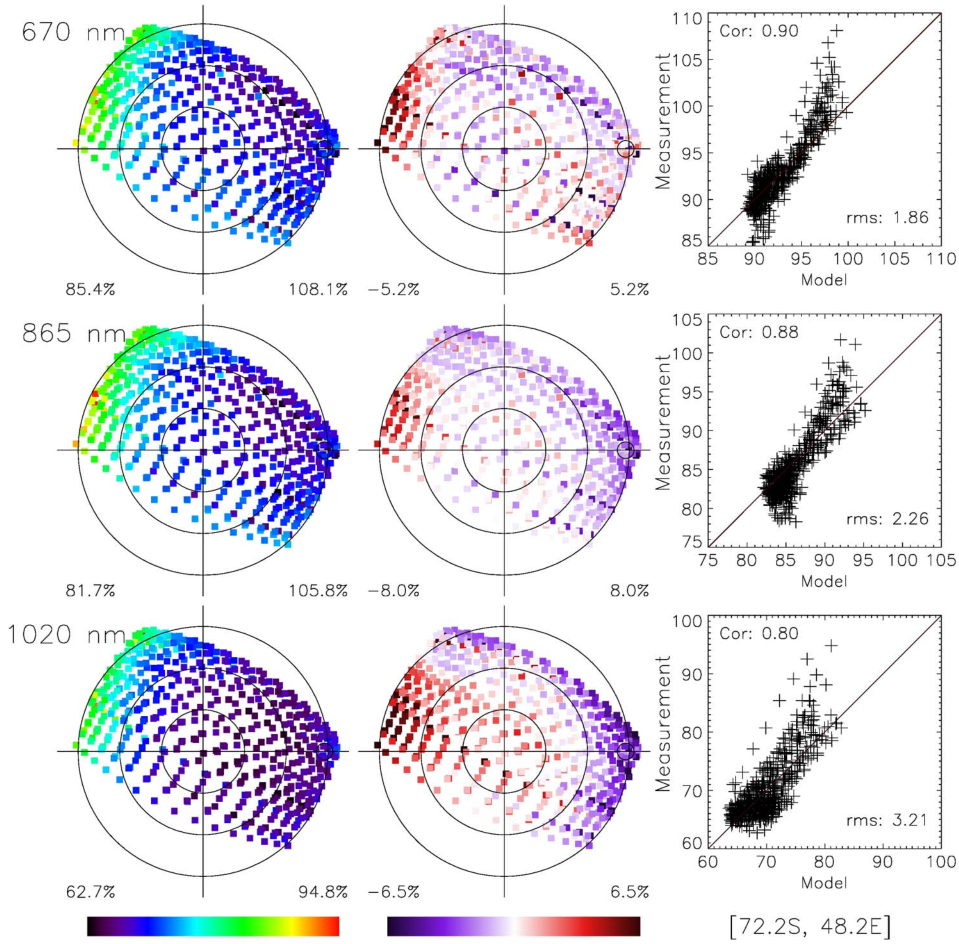

Fig. 3. Same as Fig. 1 but for a site in Antarctica ($L = 4.9$ mm and $M = 3.1 \times 10^{-8}$) and measurements acquired during December 2005.

here uses only two free parameters, for the full set of spectral bands.

The performance of ART is evaluated against a small sample of POLDER-3/PARASOL measurements in Greenland (69.4 N, 40.9 W) and Antarctica (72.2 S, 48.2 E) as shown in Figs. 1–4. As expected, the reflectance generally decreases with increasing wavelength. This is a direct consequence of the light absorption by ice grains that is close to zero in the visible and increases with wavelength. In POLDER-3 data, the snow absorption is evident at 865 nm, but much stronger for the 1020-nm channel. Figs. 2 and 4 demonstrate that the spectral signature of the snow reflectance is well reproduced by the model, after adjustment of the free parameters.

Let us now look at the directional signature. Looking at specific azimuth planes (Figs. 2 and 4), it is clear that the principal plane shows the largest directional signature. This is similar to what is observed over other land surfaces. However, the reflectance angular signature is very different: Over bare soil or vegetated surfaces, the maximum of reflectance is observed in the backscattering direction. Here, the largest reflectance is observed in the forward scattering direction, particularly at large viewing angles. Interestingly, the longer wavelength channel shows a lower reflectance, and it is also more anisotropic.

The proposed model is able to reproduce experimental results in a correct way. The largest deviations between the model and the measurements are in the forward scattering direction, for large zenith viewing angles. The correlation coefficients between experimental results and measurements are high. Figs. 1 and 3 provide (right column) the correlation coefficients and correlation plots for the full set of directions. We note that, although the correlation is high, the best fit slope is larger than 1, in particular over the Greenland site. The measurements produce more anisotropic reflectances than the model does. We received similar results for other locations in Greenland and Antarctica. On the other hand, the directional signatures of reflectance for pixels, which contain mixtures of snow and vegetation differ from those shown here. Therefore, the use of the model presented here shall be restricted to regions free of bare soil, forest, or any vegetation.

IV. Conclusions and Outlook

We have checked the performance of the radiative transfer snow model based on the asymptotic solution of the radiative transfer equation valid at snow single scattering albedo close to one [10] using satellite (POLDER) measurements over Greenland and Antarctica. We found that the model indeed can be used to describe both the spectral and directional signatures of targets that are completely covered by snow. The deviations of the model from measurements are below 10%, and correlation coefficients are above 0.85 for most cases that we analyzed, although the model results are somewhat less anisotropic than the

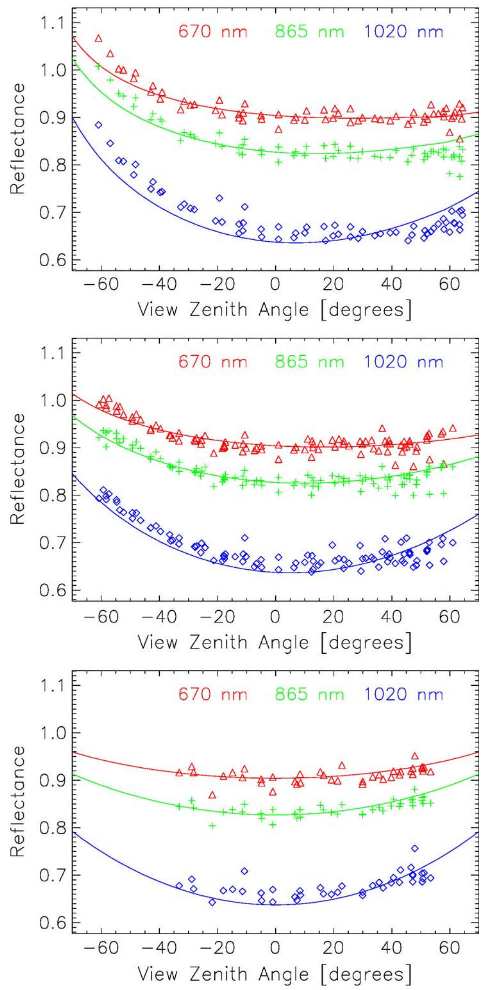

Fig. 4. Same as Fig. 2 but for the site of Fig. 3. Solar zenith angle varies between 54 and 64°.

observations, in particular in the forward scattering direction at large zenith viewing angles. The model cannot reproduce the observed directional signature of forest with a snow-covered surface. In such cases, the target RF must be modeled in a more complex way using a mixture of snow and other relevant kernels. The results obtained confirm that snow shows a directional signature that is very different than that of other land surfaces, with a maximum in the forward scattering direction [2]. The directional signature is, in relative terms, much smaller than that of vegetation or bare soil but nevertheless significant so that it must be accounted for with models of directional reflectance such as the one validated in this letter. We found that the values of the parameters L and M of the model range between 3–5 mm and $3 - 6 \times 10^{-8}$, respectively, for the days and locations considered in this letter. Future development of the model discussed here must be focused on the improvement of the model in the forward scattering direction at large view zenith angles.

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